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A hybrid partial and general equilibrium modeling approach to assess the hydro-economic impacts of large dams – The case of the Grand Ethiopian Renaissance Dam in the Eastern Nile River basin

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A B S T R A C T

A novel integrated hydro-economic modeling framework that links a bottom-up partial equilibrium (engineering) model with a top-down (economic) general equilibrium model is developed for assessing the regional economic impacts of water resources management and infrastructure development decisions in a transboundary river basin. The engineering model is employed first to solve the water allocation problem for a river system in a partial equilibrium setting. The resulting system-wide changes in optimal water allocation are subsequently fed into the general equilibrium model to provide an economy-wide perspective. This integrated hydro-economic modeling framework is illustrated using the Eastern Nile River basin as a case study. The engineering-based stochastic dual dynamic programming (SDDP) model of the Eastern Nile basin is coupled with the computable general equilibrium (CGE) model GTAP-W to assess the economy-wide impacts of the Grand Ethiopian Renaissance Dam (GERD) on the Eastern Nile economies.

1. Introduction

There are essentially two approaches to assess the economic performance of major hydraulic infrastructure projects like dams. Both approaches rely on a with-or-without analytical framework where the basic principle is to compare the additional benefits and cost “with” the project to those “without” the project. The two approaches however differ in the underlying model, which can either be a general or a partial economic equilibrium model. In either case, general equilibrium models are best used to determine the economy-wide impacts of a project (Robinson et al., 2008; Wittwer, 2009; Ma et al., 2015), whereas partial equilibrium models typically focus on the basin-wide economic consequences of the project in basin-specific sectors (Jeuland, 2010a, 2010b; Whittington et al., 2005; Block and Strzepek, 2010; Goor et al., 2010; Arjoon et al., 2014).

There are pros and cons to both modeling approaches. General equilibrium (GE) models, like Computable General Equilibrium (CGE), consider the entire economy as a complete, interdependent system, therefore providing an economy-wide perspective. The net benefits of a policy intervention are maximized subject to labor and capital constraints, including natural capital such as water resources (Dellink et al., 2012). However, CGE models are highly aggregated and their results may fail to shed light on relevant hydrological details (Brouwer and Hofkes, 2008). Moreover, CGE models are often criticized as being insufficiently validated and often relying on parameters that are not econometrically estimated (Beckman et al., 2011). Examples of applications of CGE models to hydraulic infrastructure include Egypt's High Aswan Dam (HAD) (Strzepek et al., 2008) and Australia's Traveston dam (Wittwer, 2009).

Partial equilibrium (PE) models do not consider the often complex feedbacks between the direct and indirect economic impacts of an infrastructural project and are therefore unable to assess its economy-wide consequences. However, unlike CGE models, PE models provide a more detailed representation of the water resources system with

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spatially distributed supply sources and demands that are interconnected through arcs representing the river network (Harou et al., 2009). When framed as an optimization problem, a PE model will seek to maximize the water related system-wide benefits in specific economic sectors like agriculture and hydropower that are subject to hydrologic, physical, environmental and policy constraints (Cai et al., 2003). Several studies have analyzed the economic effects of hydraulic infrastructure developments using PE models (see e.g. Jeuland, 2010a; Whittington et al., 2005; Block and Strzepek, 2010; Goor et al., 2010; Tilmant and Kinzelbach, 2012; Bielsa and Duarte, 2001; Bekchanov et al., 2015).

This paper proposes an innovative hybrid modeling framework to assess the economy-wide impacts of large-scale hydraulic infrastructure, whilst providing an engineering economics understanding of the hydrologic system. In other words, the proposed framework aims at reconciling two different scales of analysis: economy-wide and river basin-wide. This is achieved by coupling a CGE model covering the whole economy of a region with a detailed PE model focusing on the sub-region where the infrastructure is planned. Optimal water allocation policies are first determined by the PE model, and then used as input into the CGE model to assess the impacts on the rest of the economy. This coupling enriches the CGE model with relevant hydrologic detail and allows capturing interactions between water and energy dependent sectors, therefore increasing the scope of the approach and improving the validity and reliability of the CGE model.

The proposed integrated modeling framework is illustrated using the Grand Ethiopian Renaissance Dam (GERD) in the Blue Nile River basin as a case study. The dam constitutes the centerpiece of Ethiopia's five-year Growth and Transformation Plan (GTP) (2010/11–2014/15) that targets boosting the country's hydropower generating capacity (MoFED, 2010). The project has been a source of concern for downstream countries Sudan and Egypt. Situated in an arid environment with sparse and insignificant rainfall, Egypt and Sudan are heavily dependent on the Nile for their water supply. With annual water withdrawals of 55.5 km^3 and 16.1 km^3, respectively (Jeuland, 2010a), Egypt and Sudan almost exclusively use all the Nile waters. The €3.34 billion hydro-electric dam currently being built in the Blue Nile River, close to the Ethiopian border with Sudan, has a design capacity of 6000 MW and is reported to be able to produce 15.1 TWh/year upon completion (MDI, 2012). It will have a height of 145 m and a total storage volume of 74 km^3, and is assumed to be used for power generation only. This increases the country's power supply by about 150 percent and would mean a substantial additional energy source for the Ethiopian economy, enough to meet domestic as well as export demand for electricity. Currently, the country is exporting power to North Sudan and Djibouti and plans to expand its export to other neighboring countries. The country's energy export sales are forecasted to grow from 1445 GWh in 2013 to 35,303 GWh by 2037 (EEPCO, 2013). In fact, Ethiopia is considered one of the major potential exporters of power in the East African Power Pool (EAPP) region that comprises of twelve countries (EAPP, 2014). The domestic demand for electricity is forecasted to increase rapidly from 6.3 TWh/year in 2013 to 40.5 TWh/year in 2023 (EEPCO, 2013). Likewise, total electricity generation from several planned and committed hydro, wind and geothermal power plants is forecasted to increase from about 9.7 TWh/year to 65.7 TWh/year in 2023 and 146.7 TWh/year in 2037 (EEPCO, 2013) to meet the country's growing domestic and export demand for electricity.

Some studies have quantified the economic benefits of the GERD in a partial equilibrium setting using a hydro economic modeling approach (Arjoon et al., 2014; Jeuland et al., 2017; Satti et al., 2015; Basheer et al., 2018). Other studies employed a CGE modeling approach to estimate the economic benefits of the dam in the Eastern Nile countries (Ferrari et al., 2013; Kahsay et al., 2015, 2018). This study applies a hybrid modeling framework to assess the economic transboundary impacts of the GERD on the Nile economies, and combines the stochastic dual dynamic programming (SDDP) model of the Eastern Nile basin countries (Goor et al., 2010) and the CGE model Global Trade Analysis Project for Water (GTAP-W) (Calzadilla et al., 2010) using the GTAP Africa database for the Nile basin countries. More specifically, the study integrates an SDDP model of the GERD (Arjoon et al., 2014) and a CGE model of the dam (Kahsay et al., 2015) developed, respectively, to evaluate the water system wide and the economy wide effects of the dam in the Eastern Nile countries. The novelty and value added of the hybrid integrated modeling framework presented in this study is that the coupling of the two models generates new information at interconnected spatial scales that would not have been available based on the two models separately. Such coupling has furthermore never been attempted before in the Nile Basin, nor in any other transboundary river basin as far as we know.

The paper is organized as follows. Section 2 presents the integrated modeling framework. Section 3 discusses the results of the hybrid modeling approach and conclusions are drawn in Section 4.

2. Integrated modeling framework

In this section, first the partial equilibrium and general equilibrium modeling approaches are described separately. This is then followed by a description of the hybrid integrated modeling framework.

2.1. Partial equilibrium modeling

Partial equilibrium (PE) models generally rely on a network representation of the water resources system to physically connect water demands and supplies. The network is made up of water storages (lakes, reservoirs, groundwater), transmission links (rivers, canals, pipes) and demand nodes. There are essentially two approaches to allocate water in the network: simulation or optimization. Simulation models are mainly descriptive and typically try to answer 'what if' questions. This approach must be seen as an extension of simulation-based models in which water demands and allocation policies are additional inputs. Optimization-based PE models, on the other hand, are prescriptive in that they propose the 'best' allocation policies. See Heinz et al. (2007), Brouwer and Hofkes (2008) and Harou et al. (2009) for reviews of such PE modeling approaches.

A typical optimization-based PE model will seek to maximize system-wide net benefits Z over a given planning period subject to hydrologic, physical and institutional constraints. Mathematically, the problem can be written as:

$$max\ Z = E\left[\sum_{t=1}^{T} b_t(x_t, u_t) + v(x_{T+1})\right] \tag{1}$$

subject to

$$g_t(u_t) \le 0 \quad \forall\ t \tag{2}$$

$$h_t(x_t) \le 0 \qquad \forall\ t \tag{3}$$

$$x_{t+1} = f_t(x_t, u_t) \quad \forall\ t \tag{4}$$

Where

- $E$is the statistical expectation operator for the random data processes such as natural inflows, commodity prices, etc.
- $b_t(.)$is the aggregated net benefits from water allocations during time period t
- x_t is the vector of state variables (e.g. reservoir storages in the network, natural inflows)
- $u_t$is the vector of allocation decisions (e.g. reservoir releases, spills, water withdrawals, etc.)
- $v(.)$is a terminal value function at the end of the planning period. This function, which must be seen as a boundary condition, helps preventing the reservoir depletion that would occur at the end of the planning period

- g_t is a set of functions constraining the allocation decisions (e.g. upper and lower bounds)
- h_t is a set of functions constraining the state variables (e.g. upper and lower bounds)
- $f_t$is a state-to-stage transformation function (e.g. mass balance equation).

The solutions to this optimization problem are the optimal allocation decisions(u_t^*), the system trajectories (reservoir storagess_t^*) and the shadow prices(λ_t^*) associated with the constraints (2)–(4).

2.2. General equilibrium modeling

CGE models are best suited to analyze the direct as well as indirect economic impacts of large-scale policy interventions such as big dams on interconnected economic systems (Robinson et al., 2008). Price endogeneity and market-based interactions among economic agents (e.g. consumers providing the labor in the labor market necessary to produce the goods and services traded in the goods and services markets) constitute major features of CGE models that render them capable to examine the total economic impacts of policy interventions on multiple markets at the same time. The general equilibrium perspective that characterizes CGE models hence provides insights into the economy-wide impacts of water resources policy. Several studies have used CGE models to examine a wide range of water related issues (e.g. Seung et al., 1998; Seung et al., 2000; Gomez et al., 2004; Diao et al., 2005; Brouwer et al., 2008; Dellink et al., 2012). Johansson (2005), Dudu and Chumi (2008), Brouwer and Hofkes (2008) and Dinar (2014) provide reviews of CGE models applied to water resources management.

Theoretically, water can enter both the production and consumption function in a CGE model. Below, a simplified representation of the model - without government and international trade - is given to highlight its main features. Firms maximize profits under the restriction of a given production technology and at given prices p. Following a nested-Constant Elasticity of Substitution (CES) production function f (Eq. (7)), output Y of each sector is produced by intermediate deliveries from all J sectors (Y^{ID}), N factors of production such as labor and capital services (E^{N}), and available raw water (W), under production technology characterized by V elasticities of substitution (σ) in different "nests" of the production function. Each producer produces one unique output from the inputs. Assuming full competition and constant returns to scale technologies, excess profits are assumed to be zero (Eq. (8)):

$$Y_{j,t} = f\,(Y_{1,j,t}^{ID},\ ...Y_{J,j,t}^{ID},\ E_{j,t}^{1}...E_{j,t}^{N},\ W_{j,t};\ \sigma_j^1,...,\sigma_j^V) \text{ for each sector j and year t} \tag{7}$$

$$0 = \prod\nolimits_{j,t} = Y_{j,t} - \sum_{j=1}^{J} Y_{j,t}^{ID} - \sum_{n=1}^{N} (E_{j,t}^{n}) - W_{j,t} \text{ for each sector j and year t} \tag{8}$$

Consumers, represented by a single representative household, maximize utility (Eq. (9)) under a budget constraint (Eq. (10)) at given prices and given their initial endowments of production factors(labor) (E^N) and water (W). In the GTAP model, for example, consumers first allocate income between consumption and savings according to a Cobb-Douglas (CD) function h. A nested, non-homothetic constant difference of elasticities (CDE) utility function g is used to maximize welfare derived from consumption. Preferences are characterized by elasticities of substitution (β) and elasticities of income (γ) in different "nests" of the utility function. The consumption bundle that maximizes welfare includes water services from the water services sector, $C_{w,t}$ in Eq. (9).

$$U_t = h(S_t,\ g(C_{1,t}...C_{w,t}...C_{J,t}\ ;\ \beta^1...\beta^W,\ \gamma^1...\gamma^W)) \tag{9}$$

$$\sum_{j=1}^{J} (C_{j,t}) + S_t = \sum_{n=1}^{N} (\bar{E}_t^n) + \bar{W}_t \tag{10}$$

On the consumption side, Eq. (10) identifies that income generated from the employment of the endowments (labour and water) equals consumption and savings since there are no excess profits on the production side.

Market clearance is assumed for the goods market (Eq. (11)), the endowments market (Eq. (12)) and the water market (Eq. (13)) for each year. In the goods market, total output is equal to the sum of internal deliveries$Y_{j,t}^{ID}$, final consumption $C_{j,t}$ and investment demand $I_{j,t}$.

$$Y_{j,t} = \sum_{j=1}^{J} Y_{j,t}^{ID} + I_{j,t} + C_{j,t} \text{ for each sector j and year t} \tag{11}$$

In the endowments markets, total demand for endowments is equal to the exogenous supply of endowments in each year (marked by the bar above the variable):

$$\sum_{j=1}^{J} E_{j,t}^{n} = \bar{E}_t^n \text{for each endowment n and year t} \tag{12}$$

$$\sum_{j=1}^{J} W_{j,t} = \bar{W}_t \text{for each year t} \tag{13}$$

Finally, investments equal savings for each year (Eq. (14)):

$$S_t = \sum_{j=1}^{J} I_{j,t} \text{for each year t} \tag{14}$$

The dynamics of the model are driven by scenario-specific, exogenous growth of the total endowments of factors of production $\bar{E}^n$ and water $\bar{W}$, and by an increase in total factor productivity (that is not shown in the equations above).

The first order condition for profit maximization (Eq. (8)) is that the factors of production, including water, are allocated across alternative productive uses such that their marginal values are equal across all uses and equal to their market prices. Hence, our CGE model treats raw water as a normal factor of production with a market price. Econometric models are usually used to derive the marginal productivity (and hence shadow price) of non-priced water in production processes of marketed goods and services, while surveys often underlie the estimation of marginal willingness to pay for the enjoyment of non-priced water resources in a household's welfare function. Market clearing for outputs and inputs is the main mechanism to solve the set of mathematical equations in a CGE model, setting production equal to consumption, and investments in capital accumulation through time occur through savings.

2.3. Integrated modeling framework

The integrated modeling framework links a bottom-up stochastic PE model (SDDP) with a top-down CGE model (GTAP-W) for assessing the transboundary economic impacts of water resource management and infrastructure development in a shared river basin. The PE model is used to solve the water allocation problem for a river system in a partial equilibrium setting. The resulting water system-wide changes in optimal water allocation (e.g. agricultural output and hydropower generation) are then used as inputs in the CGE model to derive an economy-wide perspective on the total direct and indirect economic impacts of the water resources management and development decisions in the water system. Hence, the outputs of the PE model serve as inputs into the CGE model.

The PE model seeks to maximize the expected basin-wide net benefits from irrigated agriculture and hydropower generation taking into account the hydrologic uncertainty. The optimization problem is solved using a stochastic dual dynamic programming algorithm (SDDP)

(Tilmant et al., 2008). This algorithm removes the computational burden associated to dynamic programming by constructing a locally accurate approximation of the objective function. To achieve this, the algorithm relies on an iterative process involving two phases. In the optimization phase, the approximation of the objective function is constructed stage by stage as the algorithm progresses backward. Then, once reaching the first stage, a forward simulation phase is initiated in order to test how good the approximation is. In this phase, the decision-making problem is solved forward for a given number of stream flow sequences that capture the hydrologic uncertainty. At the end of the simulation phase, the algorithm provides time series of reservoirs' releases, evaporation losses, spillages losses, water withdrawals for off-stream uses as well as the shadow prices of the constraints imposed on water use and allocation in equations (2)–(4). In this study, the planning period is 10 years, the decision-making problem is solved on a monthly time step (T = 120) and there are 30 hydrologic sequences in the simulation phase. As explained in Tilmant and Kinzelbach (2012), to avoid the influence of the boundary conditions – initial storage and terminal value function - on the allocation decisions, the results are analyzed for year five only (t = 61, …, 72).

Due to the stochastic nature of this PE model, each result is characterized by a vector of 30 values than can be used to trace out the empirical statistical distribution. When coupling the stochastic PE to the CGE model, it is therefore possible to assess the economy-wide impacts of a project under contrasting hydrologic conditions (e.g. dry versus wet years). Ignoring potential long-term hydrologic persistence and non-representativeness due to year-to-year variation, the annual stream flow sequence (q_p) corresponding to a particular non-exceedance probability (p) can be directly selected from the set of streamflow sequences used in the simulation phase of the optimization algorithm. With this approximation, the associated allocation decisions ($X|q_p$) can be extracted and aggregated at country and annual time step scale before being transferred to GTAP-W. This procedure is illustrated in Fig. 1 where the economy-wide impacts are assessed under, say, three different hydrologic conditions corresponding to the kth, pth and lth percentiles of the statistical distribution of the natural river discharges at the basin's outlet during year five. Imagine, for example, that the analysis must be carried out for dry conditions with a return period of 10 years. The PE results would in that case correspond to the allocation decisions taken with an annual stream flow sequence with a non-exceedance probability of 10 percent. In this study, the economy-wide impacts of GERD are assessed for dry, normal and wet hydrologic conditions corresponding to the 10th percentile, average, and 90th percentile of the statistical distribution of the Nile River outflows. Table 1 lists the allocation decisions that are transferred from the PE model to the GTAP-W model.

Table 1
Information transferred from SDDP to GTAP-W.

Decision	Units	Aggregation
Irrigation withdrawal	Million m^3/crop/node/month	Country scale
Hydropower generation	GWh/power plant/month	Annual time step

More specifically, the PE model of the Eastern Nile Basin includes 9 irrigation demand sites and 12 hydropower plants located in the three Eastern Nile countries: 2 irrigation sites and 4 hydropower plants in Ethiopia, 6 irrigation sites and 5 hydropower plants in Sudan, and 2 irrigation sites and 3 hydropower plants in Egypt. Fig. 2 depicts the schematic overview of the nodes comprised of all major reservoirs, hydropower plants and irrigation schemes as well as the river reaches considered in the model. The model solves the water resources allocation problem on a monthly time step and using 30 different hydrologic scenarios to capture the short-term (seasonal) natural variability of river discharges throughout the system. The 30 hydrologic scenarios are generated by a built-in autoregressive (AR) model of order one whose parameters are also needed to construct the approximation of the objective function. This built-in AR model plays an essential role in the SDDP algorithm, but it is unable to handle the long-term persistence that characterizes the flow regime of rivers like the Nile. This shortcoming must be weighed against the benefits of the joint optimization

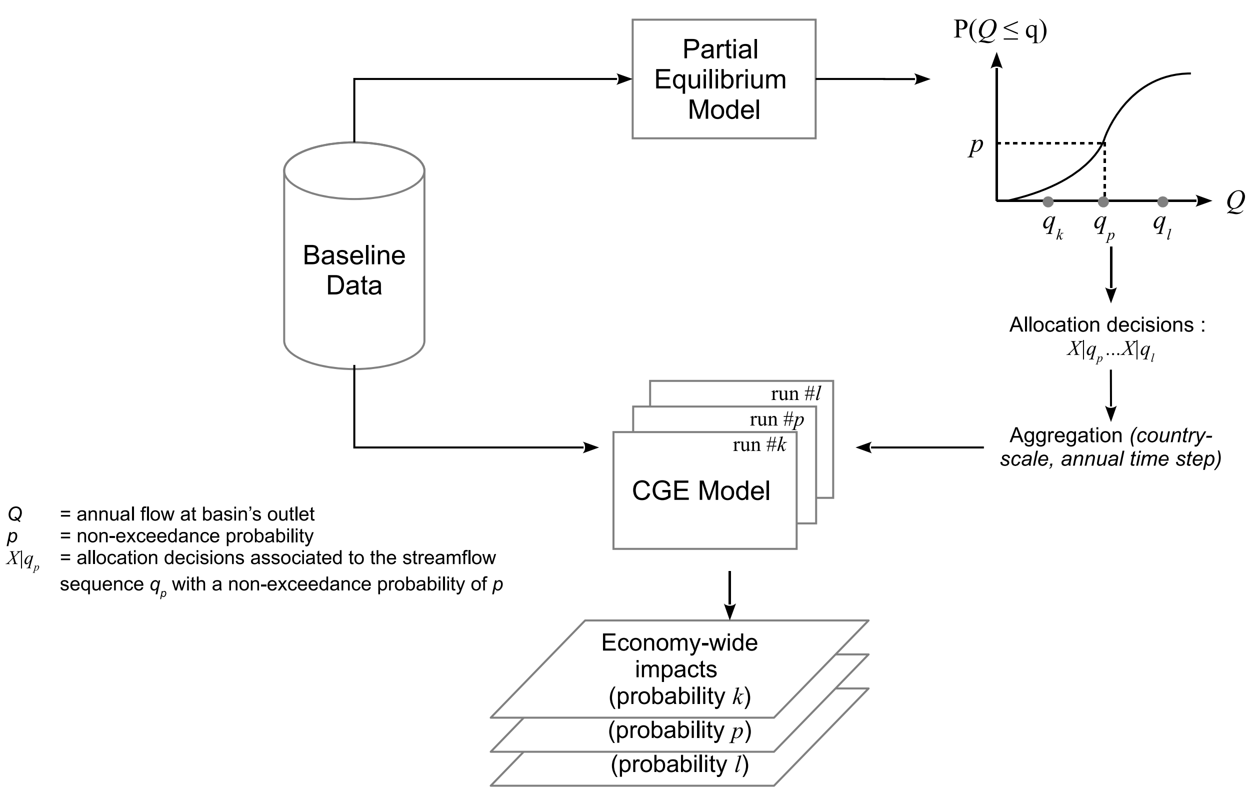

Fig. 1. Overview of the integrated modeling framework.

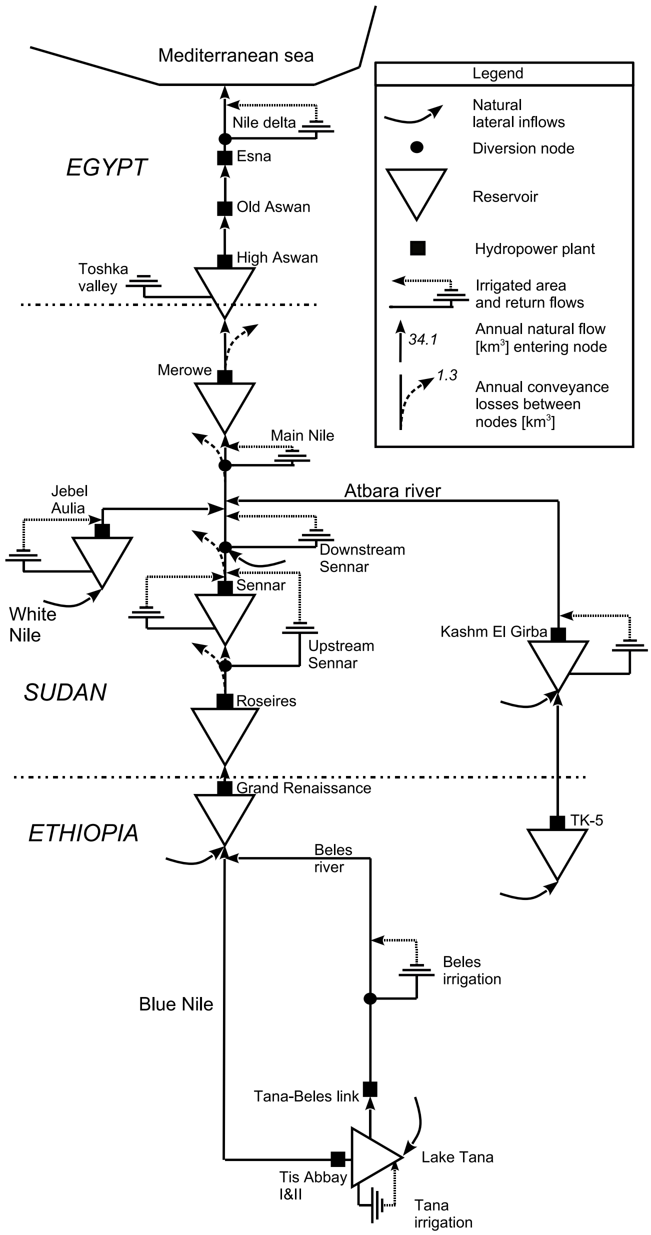

Fig. 2. Schematic overview of the Eastern Nile Basin in the PE model.

of all allocation decisions in the system. See Arjoon et al. (2014) for a detailed mathematical description of the model.

The CGE model applied in this study is the Global Trade Analysis Project (GTAP) model (Hertel, 1997), developed at the Center for Global Trade Analysis, Purdue University, USA, for use in global trade analysis. GTAP provides a global modeling framework and a common global database, providing the opportunity to conduct comparable model implementations and policy simulations. GTAP is a static-comparative, multi-region, multi-sector CGE model of the world economy that examines all major aspects of an economy via its general equilibrium feature. The GTAP model comprises accounting relationships, behavioral equations and global sectors required to complete the model. The accounting relationships of the model ensure the balance of receipts and expenditures for every agent identified in the economy, whereas the behavioral equations specify the behavior of optimizing agents in the economy (i.e. production and demand functions) based on microeconomic theory (Brockmeier, 2001).

The analysis presented here is the version of the GTAP-W model (Calzadilla et al., 2010) that distinguishes between rainfed and irrigated agriculture and incorporates water as a factor of production directly substitutable in the production process of irrigated agriculture. To account for water, the model disaggregates the agricultural land endowment in the standard GTAP database into rainfed land, irrigated land and irrigation water. Following Calzadilla et al. (2011), the relative share of rainfed and irrigated agriculture in total production is used to split the land rent in the original GTAP database into a value for rainfed land and a value for irrigated land for each crop in each region. In the next step, the ratio of irrigated yield to rainfed yield is used to split the value of irrigated land into the value of irrigable land and the value of irrigation water. The production system is set up as a series of nested constant elasticities of substitution (CES) functions combined through substitution elasticities (see Fig. 3).

The GTAP-W model of the Eastern Nile region uses the GTAP Africa Data Base, which is divided for the purpose of the present study into seven regions: Ethiopia, Sudan including South Sudan, Egypt, the Equatorial Lakes (EQL) region, Rest of North Africa, Rest of Sub-Sahara Africa and Rest of the World (ROW). Since the focus of the study is exclusively on the Eastern Nile region that is directly affected by the GERD, the regional aggregation highlights the importance of the three Eastern Nile countries (see Appendix A). The 57 sectors in the GTAP Africa Data Base are aggregated for the purpose of this study into 17 sectors, of which 8 are agricultural sectors and 9 non-agricultural sectors (see Appendix B).

To ensure that the PE and CGE models start from the same baseline conditions in the Nile basin and apply the same crop yield functions, detailed data on land and water use as well as crop yields specified per country are derived from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) database developed at the International Food Policy Research Institute (IFPRI) (Rosegrant et al., 2008). The IMPACT data provides detailed data for the year 2000 and simulation data until the year 2050 with respect to irrigation water use, crop yields and cropped area, distinguishing between 20 rainfed and irrigated crops and 281 food processing units (FPU's) for 115 economies and 126 river basins. The FPU's constitute spatial units defined by political boundaries and major river basins.

Fig. 4 provides a flow diagram of the process of linking the SDDP and GTAP-W models of the Eastern Nile basin. In a first step, detailed IMPACT data on land use in irrigated and rainfed agriculture, irrigated and rainfed yield, water use in irrigated and rainfed production specified per country are used to calibrate and benchmark the baseline of the SDDP and GTAP-W models. The SDDP model is then employed in a second step to solve the water allocation problem in the Eastern Nile basin with GERD online in a dynamic setting. The SDDP-derived changes in optimal water allocation, agricultural output and hydropower generation are then in a final step implemented in the CGE model to estimate the direct and indirect economic impacts of the dam on the Eastern Nile countries. In principle, a feedback loop whereby the outputs of the GTAP-W model are fed back as inputs into the SDDP model could be imagined. This procedure would update land and water use and crop yield and thereby further refine the optimization procedure. However, this feedback procedure is deferred to future study.

3. Results

3.1. Partial equilibrium results

The PE model is employed to identify changes in hydropower generation and irrigation water supply (crop production) in the Eastern Nile countries due to GERD operation. Table 2 lists the main results corresponding to the driest, average and wettest hydrologic conditions in the Eastern Nile Basin. The GERD is not expected to entail a significant reduction of water flowing downstream as the evaporation rates in the Upper Blue Nile are negligible compared to the rest of the Eastern Nile Basin. As a matter of fact, our simulated evaporation losses from GERD (672 MCM/y) correspond to merely 4 percent of the

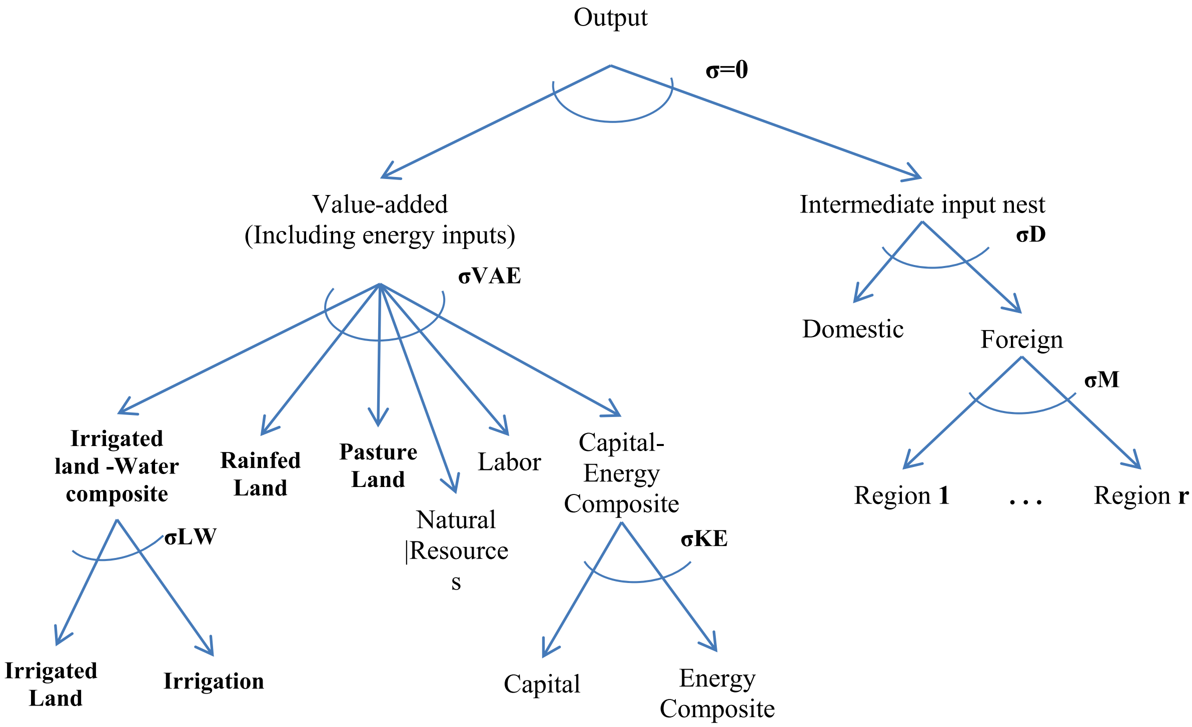

Fig. 3. GTAP-W nested production structure.

combined evaporation from the other man-made reservoirs in the Eastern Nile basin.

The PE model results indeed reveal that water supply and hence crop production remains unchanged in Egypt and more or less stable in Ethiopia, while Sudan would gain substantial improvements in irrigation water use as well as land use and hence crop production with GERD operating upstream (Table 2). Sudan gains a substantial increase in water and land use and crop output mainly during dry hydrological conditions and to a lesser extent during average hydrological conditions. Irrigation water, irrigated land use, and crop output in the country increase by 2.8–79.5 percent, 1.7–79.5 percent and 0.3–79.5 percent, respectively, during dry hydrological conditions. The country gains a 0.1 to 47.8 percent increase in irrigation water use, land use and crop output during average hydrological conditions. However, Sudan's gains in terms of water and land use and crop output during wet hydrological conditions are relatively low (9.1–15.1%) and limited to a few crops (other cereals and other crops). Thus, Sudan benefits from increased water availability during dry years from water stored in the GERD reservoir during wet years. Overall, Sudan gains 4.6, 2.6 and 0.9 km^3 of irrigation water during dry, average and wet hydrological conditions, respectively, with GERD operating upstream. With the baseline irrigation water use level in Sudan standing at 12.9, 15.4 and 17.3 km^3 during dry, average and wet years, the total water use in the country due to GERD operation increases to 17.5, 18 and 18.2 km^3,

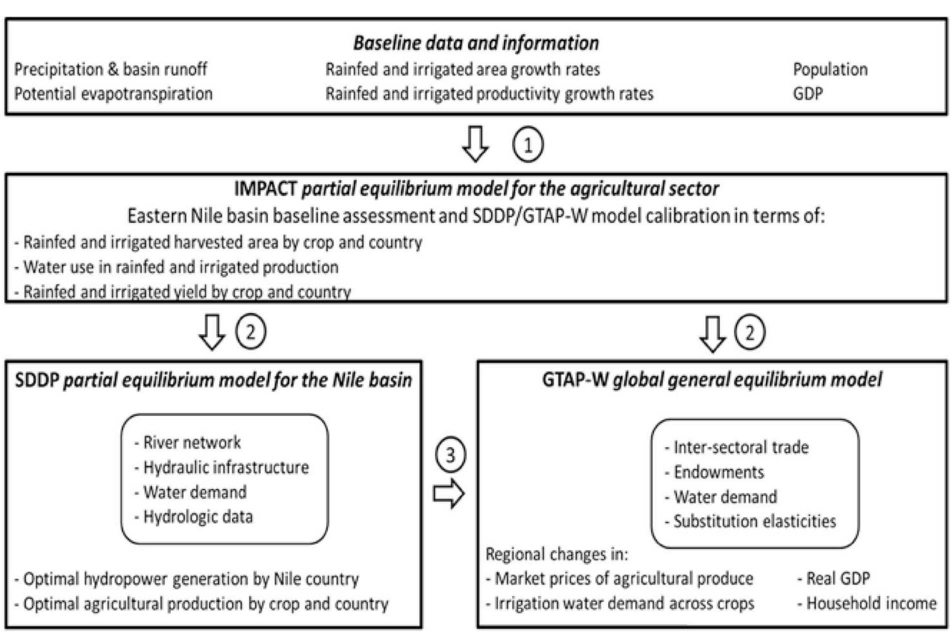

Fig. 4. Integrated modeling framework.

Table 2
Estimated percentage change in irrigation water allocation and irrigated land use across crops and optimal crop output due to GERD based on the PE model[a].

	Change in irrigation water use (%)					
	Ethiopia			Sudan (pre 2011)		
	Hydrologic condition			Hydrologic condition		
	Dry	Average	Wet	Dry	Average	Wet
Rice	0.0	0.0	0.0	19.8	3.5	0.0
Wheat	0.0	0.0	0.0	10.7	0.3	0.0
Other cereals	0.0	0.0	0.0	57.5	29.5	9.2
Other crops	0.0	0.0	0.0	79.5	47.8	15.1
Fruits & vegetables	−3.1	−0.8	0.0	2.8	0.1	0.0
Oilseeds	0.0	0.0	0.0	9.7	0.3	0.0
Sugar cane, sugar beet	0.0	0.0	0.0	20.3	1.9	0.0
Total	**−1.1**	**−0.3**	**0.0**	**35.4**	**16.6**	**5.4**

	Change in irrigated land use (%)					
	Ethiopia			Sudan (pre 2011)		
	Hydrologic condition			Hydrologic condition		
	Dry	Average	Wet	Dry	Average	Wet
Rice	0.0	0.0	0.0	19.8	3.5	0.0
Wheat	0.0	0.0	0.0	10.7	0.3	0.0
Other cereals	0.0	0.0	0.0	57.5	29.5	9.1
Other crops	0.0	0.0	0.0	79.5	47.8	15.1
Fruits & vegetables	−1.1	−0.3	0.0	1.7	0.1	0.0
Oilseeds	0.0	0.0	0.0	9.7	0.3	0.0
Sugar cane, sugar beet	0.0	0.0	0.0	20.3	1.9	0.0
Total	**−0.5**	**−0.1**	**0.0**	**37.8**	**18.7**	**6.0**

	Change in crop output (%)					
	Ethiopia			Sudan (pre 2011)		
	Hydrologic condition			Hydrologic condition		
	Dry	Average	Wet	Dry	Average	Wet
Rice	0.0	0.0	0.0	19.8	3.5	0.0
Wheat	0.0	0.0	0.0	10.7	0.3	0.0
Other cereals	0.0	0.0	0.0	57.3	29.4	9.1
Other crops	0.0	0.0	0.0	79.5	47.8	15.1
Fruits & vegetables	−1.3	−0.3	0.0	0.3	0.0	0.0
Oilseeds	0.0	0.0	0.0	9.7	0.3	0.0
Sugar cane, sugar beet	0.0	0.0	0.0	20.3	1.9	0.0
Total	**−0.3**	**−0.1**	**0.0**	**20.7**	**6.6**	**2.0**

[a] No changes in irrigation water use, irrigated land use and crop output are observed for Egypt.

Table 3
Water balance of the Eastern Nile as used in the PE model (km3/year).

	Without GERD	With GERD
Natural inflow	94.600	94.600
Natural evaporation	7.283	7.123
Evaporation reservoirs ET	0	0.672
Evaporation reservoirs SU	6.412	6.637
Consumptive use ET	0.189	0.189
Consumptive use SU	11.858	13.839
Inflow EG	68.859	66.140
Evaporation HAD	10.337	10.612
Outflow HAD	58.522	55.528

Explanatory note: ET = Ethiopia, SU = Sudan, EG = Egypt, HAD = High Aswan Dam.

respectively. The baseline water use in Sudan refers to demands in the year 2000. This is also based on a hypothetical situation that assumes full collaboration occurs across the riparian countries in the basin. Actual water uses across crops before and after the GERD are reported in Appendix D. The figures for irrigation land expansion in Sudan are in the order of 616.6, 361.5 and 132.9 thousands of hectares, respectively. The substantial increases in irrigation water and land use increases total crop output in the country by 117.8, 419.6, and 132.9 tons, respectively, during dry, average and wet hydrological conditions.

Recent studies (Arjoon et al., 2014; Digna et al., 2018) have shown that if the riparian countries were to cooperate under a scenario with large irrigation expansion in Sudan, increased water use in that country could partially be compensated by re-operating the downstream reservoirs at lower pool elevation in order to reduce evaporation losses. In this study, however, although water diversions in Sudan are increasing with GERD online, the difference is not significant enough and HAD does not require to be re-operated at lower pool elevation in order to reduce evaporation losses.

Table 3 lists the main terms of the mass balance in the basin. Those volumes correspond to the average annual flows derived from the 30 synthetically-generated hydrologic scenarios used in the simulation phase of the partial equilibrium model (SDDP). Each simulation is 10 years long and we only analyze the results of year 5 to avoid distortions caused by boundary conditions. Hence, for year 5 we have 30 simulations, and the terms of the mass balance are the annual averages over these 30 simulations. When losses through consumptive uses are accounted for in Sudan and Ethiopia, the average annual flow entering Egypt is 66 km^3. The majority of those losses are due to irrigation water withdrawals in Sudan. Subtracting the evaporation losses at HAD (10.6 km^3), the annual volume of water available to Egypt is 55.53 km^3, which is in accordance with Egypt's share as per the 1959 treaty (55.5 km^3), and very close to IMPACT data on Egypt's water demand in the agricultural sector (53.7 km^3). Our results indicate that a further increase of consumptive uses upstream, beyond those considered in this study, combined with a lack of cooperation, would likely affect Egypt's water supply.

When GERD is online, the downstream reservoirs on the Blue Nile and Nile can be operated at higher pool elevation since much of the inflows is now regulated. Consequently, the evaporation losses from those reservoirs increase by 1.161 km^3/year (Table 3), therefore reducing the inflows reaching Egypt.

The SDDP model results also reveal that the GERD will substantially boost the energy generation in the Eastern Nile countries. With GERD online, hydropower generation in Ethiopia and Sudan will increase by 354.9–765.4 and 4.8–16.6 percent or 10.5 to 17.8 and 0.4 to 0.8 TWh/year respectively depending on the hydrological condition that may prevail in the basin, while Egypt would see little change (0.2–0.7% or 0.03–0.06 TWh/year) in the status quo (Table 4). Under average hydrological conditions, hydropower generation in Ethiopia and Sudan increases by 505.1 and 6.4 percent or 14.4 and 0.5 TWh/year

Table 4
The expected impact of GERD on hydropower generation and overall electricity production based on the PE model.

	Hydropower generation[b]									Share of hydropower in electricity production[a] (%)	Change in electricity generation due to GERD (%)		
	With GERD (TWh/yr)			Without GERD (TWh/yr)			Change (%)						
	Hydrologic condition			Hydrologic condition			Hydrologic condition				Hydrologic condition		
	Dry	Average	Wet	Dry	Average	Wet	Dry	Average	Wet		Dry	Average	Wet
Egypt	10.1	12.6	15.9	9.4	12.7	15.5	7.9	−0.7	2.5	8.3	0.7	−0.1	0.2
Ethiopia	12.0	17.4	23.0	1.4	2.9	5.0	773.2	510.2	358.5	99.0	765.4	505.1	354.9
Sudan	5.8	6.9	8.6	4.8	6.3	8.1	22.1	8.5	6.4	75.2	16.6	6.4	4.8

[a] World Development Indicators (2013).
[b] Tractebel Engineering GDF Suez and Coyne et Bellier, Hydrological and Reservoir Simulations Studies, GERD Project Impounding and Operation Simulations

respectively, it remains stable in Egypt. The electricity sector in the standard GTAP database is an aggregate of different power generation activities. Although the Eastern Nile basin countries derive electricity from different sources, the model has only one electricity sector. Therefore, the change in hydropower supply due to the GERD is simulated as a percentage change in the total supply of electricity. Available data shows regional variation in the source of electric power generation in the Eastern Nile Basin countries. Ethiopia and Sudan rely on hydropower for as much as 99 and 75 percent of their electric power supply, respectively, while Egypt heavily relies on natural gas and derives less than 10 percent of its electricity from hydropower (Table 4). As shown in Table 4, the change in hydropower supply resulting from GERD operation and the relative share of hydropower in total electricity production in these countries is used to induce the required policy intervention in the electricity sector. Details of changes in hydropower generation in Egypt's hydropower facilities induced by GERD are provided in Appendix C.

3.2. General equilibrium results

GTAP-W simulations are run with the following assumptions: (1) the construction of the GERD is expected to increase Ethiopia's capital stock and domestic saving by about 10 percent (Kahsay et al., 2015) regardless of the hydrologic conditions; (2) electricity supply, irrigation water use and irrigated lands vary according to the hydrologically-dependent allocations determined by the PE model (see section 3-1). Table 5 presents the simulation scenarios considered for the GTAP-W model implementation, the results of which are presented below.

This section presents the results of the simulations based on GTAP-W to assess the direct and indirect economic effects of GERD operation on the Eastern Nile economies. We use changes in real GDP, market prices of agricultural produce, irrigation water demand across crops, household income and consumption expenditures and overall welfare effects relative to the baseline situation as indicators of the economic effects of the dam.

The simulation results shown in Table 6 reveal that Sudan is able to withdraw more water, particularly during the dry and average hydrologic conditions, which is the result of more constant flows in the Blue Nile. Water use in irrigated agriculture increases considerably in the agricultural sectors in Sudan. Irrigation water use increases 2.9 to 77.8 percent in Sudan's agricultural sectors during dry hydrological conditions. During average hydrological conditions, irrigation water use in Sudan increases substantially in the rice, other cereals and other crops sectors (3.5–47.6%) and increases lightly in the remaining sectors. In the case of wet hydrological conditions, water use remains stable in Sudan's agricultural sectors except for other cereals and other crops where it increases by 5.7 and 15.1 percent, respectively. Increases in irrigation water use in Sudan are more prominent for dry hydrological conditions than wet hydrological conditions. The results show demand for irrigation water remains stable in Egypt's agricultural sectors for all hydrological conditions. Similarly, irrigation water use remains stable in Ethiopia except for Fruits & vegetables sector where the demand for water decreases by 3.1 and 0.8 percent for dry and average hydrological conditions, respectively. Water demand across crops before and after the GERD is reported in Appendix E.

The changes in agricultural output due to GERD derived from the SDDP model and implemented in the CGE model as input variables are expected to influence market prices of crops. The simulation results in Table 7 show agricultural prices remain stable in Egypt and fall in Sudan. During dry hydrological conditions, agricultural prices fall in Sudan's agricultural sectors (3.3–80.9%) except in vegetables and fruits where price increases by 2.9 percent. During average hydrological conditions, agricultural prices in Sudan fall by 1–69.6 percent except in wheat and oilseeds where prices remain stable and vegetables and fruits where price increases by 2.3 percent. In the case of wet hydrological conditions, agricultural prices in Sudan decrease in other cereals and other crops (5–39.7%), increase in vegetables and fruits and sugar crops (1–7.8%) and remain more or less stable in other sectors. In Ethiopia, depending on the hydrological condition that may exist in the basin, agricultural prices are expected to rise by 2.1–15.5 percent.

Table 8 presents the effect of the GERD on real GDP and real return to unskilled labor. The simulation results demonstrate that the dam results in a higher level of real output and hence positive growth for all the Eastern Nile countries. Although all the Eastern Nile countries experience economic growth due to the GERD, the distribution of benefits favor mainly Ethiopia and to a lesser extent Sudan. Economic growth in

Table 5
Simulation scenarios in the Eastern Nile basin countries for the GTAP-W model (% change from the baseline conditions).

	Egypt			Ethiopia			Sudan (pre-2011)		
	Hydrologic condition			Hydrologic condition			Hydrologic condition		
	Dry	Average	Wet	Dry	Average	Wet	Dry	Average	Wet
Electricity supply	0.7	−0.1	0.2	765.4	505.1	354.9	16.6	6.4	4.8
Irrigation water use	0.0	0.0	0.0	−1.1	−0.3	0.0	35.4	16.6	5.4
Irrigated land use	0.0	0.0	0.0	−0.5	−0.1	0.0	37.8	18.7	6.0
Capital stock	0.0	0.0	0.0	10.0	10.0	10.0	0.0	0.0	0.0
Domestic saving	0.0	0.0	0.0	10.0	10.0	10.0	0.0	0.0	0.0

Table 6
The predicted percentage change in water demand in irrigated agriculture in the Eastern Nile countries due to GERD operation relative to the baseline year 2000 based on GTAP-W.

Crops	Dry hydrologic condition			Average hydrologic condition			Wet hydrologic condition		
	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan
Rice	0.0	0.0	19.5	0.0	0.0	3.5	0.0	0.0	0.0
Wheat	0.0	0.0	10.6	0.0	0.0	0.4	0.0	0.0	0.0
Other cereals	0.0	0.0	38.4	0.0	0.0	17.6	0.0	0.0	5.7
Other crops	0.0	−0.1	77.8	0.0	0.0	47.6	0.0	0.0	15.1
Fruits & vegetables	0.0	−3.1	2.9	0.0	−0.8	0.2	0.0	0.0	0.0
Oilseeds	0.0	−0.1	9.8	0.0	0.0	0.4	0.0	0.0	0.0
Sugar cane, Sugar beet	0.0	0.0	9.5	0.0	0.0	0.3	0.0	0.0	0.1

Egypt remains more or less stable. The basin-wide gain in real GDP due to the GERD relative to the baseline situation is about USD 2.02 to 2.73 billion. The gain in real GDP is more prominent for dry hydrological conditions (2.73 billion USD) compared to the wet hydrological condition (2.02 billion USD). On average, Ethiopia and Sudan gain USD 2.04 and USD 0.26 billion, respectively. The average gains in real GDP correspond to an economic growth rate of 11.3 and 1.5 percent in Ethiopia and Sudan, respectively compared to the baseline.

The economic growth the Eastern Nile countries experience due to the GERD tends to be pro-poor in the sense that it improves the real return for unskilled labor in these countries. The real return to unskilled labor measures the change in return to unskilled labor relative to the price index of household consumption expenditures and hence reflects trends in poverty reduction. Real return for unskilled labor improves in all the Eastern Nile countries (Table 8). Thus, the GERD is of significant importance in reducing poverty, mainly in Ethiopia and Sudan and to a lesser extent in Egypt.

The simulation results for household income and consumption expenditures are depicted in Table 9. The results reveal that Ethiopia, followed by Sudan, enjoys the largest improvement in household income and hence consumption expenditures induced by GERD operation (8.9–13.3% and 9.1–10.7%, respectively). The figures for Sudan stand at 1.2 to 7.7 percent and 0.5 to 2.2 percent, respectively. Household income and consumption expenditure remain stable in Egypt.

The overall welfare effects of the GERD, as measured by the equivalent variation (EV), i.e. the amount of income that would have to be given to an economy before building the dam so as to leave the economy as well off as it would be after the dam has been built, are substantial (Fig. 5). The total welfare gain and its distribution in the Eastern Nile countries due to GERD are more or less similar to that of real GDP. The results reveal that Egypt's economy is more responsive to a change in energy supply than water supply. For example, a one percent decline in hydroelectric supply, on average, results in a US$116.3 million welfare loss, while a one percent increase in water supply, on average, results in an almost 10 times smaller welfare gain of US$12.6 million. Thus, it appears that Egypt's economy is more constrained by energy supply than water availability. However, the potential political cost of energy versus water reduction in Egypt remains an issue that requires due consideration. The results based on a welfare decomposition analysis (Huff and Hertel, 2000) reveal that the endowment effect (i.e. increase in water stocks and built infrastructure) and technical change contribute most to the welfare gain in Ethiopia and Sudan. Welfare gains in Egypt emanate from allocative efficiency, the endowment effect and technical change.

The results show that the economy of Egypt, measured using multiple indicators including changes in the prices of agricultural products, real GDP, return to unskilled labour, household income, consumptive expenditures and overall welfare, remains stable. Based on these various economic indicators, the results thus indicate that GERD has no adverse negative effect on Egypt.

The SDDP and hence the GTAP-W model results reveal that benefits due to the GERD are more prominent during dry years. Nile flows during wet years stored in the huge GERD reservoir increase water availability downstream during dry years. With limited water storage infrastructure, Sudan located immediately downstream of the GERD benefits the most from GERD water supply during dry years. The impact of GERD is less pronounced during wet years because there is little deficit in water supply in the basin even without the GERD.

4. Discussion and conclusions

This manuscript presents a new modeling framework to assess the regional economic impacts of large hydraulic infrastructure. The proposed framework relies on the coupling of a PE model with a CGE model. The coupling enriches the CGE models and provides policy makers with new information regarding the economic consequences of hydraulic infrastructure that would otherwise be unavailable. The Grand Ethiopian Renaissance Dam on the Blue Nile is used as a case study.

The results of our analysis reveal that the GERD generates substantial economic benefits and enhances economic growth in Ethiopia and Sudan although the distribution of benefits favours mainly Ethiopia. Economic benefits in Egypt improve slightly due to GERD operation during dry hydrological conditions and remain stable during

Table 7
The predicted percentage change in the price of agricultural products in the Eastern Nile countries due to GERD operation relative to the baseline year 2000 based on GTAP-W.

Crops	Dry hydrologic condition			Average hydrologic condition			Wet hydrologic condition		
	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan
Rice	0.0	2.4	−5.3	0.0	2.2	−1.0	0.0	2.1	0.1
Wheat	0.0	5.8	−4.0	0.0	4.5	0.0	0.0	3.7	0.1
Other cereals	0.1	7.6	−80.9	0.0	5.8	−69.6	0.0	4.9	−39.7
Other crops	0.0	4.2	−17.0	0.0	3.1	−12.5	0.0	2.6	−5.0
Fruits & vegetables	0.1	15.5	2.9	0.0	7.8	2.3	0.0	5.2	1.0
Oilseeds	0.0	4.4	−3.3	0.0	3.3	0.1	0.0	2.6	0.1
Sugar cane, Sugar beet	0.1	8.0	−67.3	0.0	5.8	−25.4	0.0	4.7	7.8

Table 8
The predicted effect of GERD operation on real GDP and real return to unskilled labor relative to the baseline year 2000 based on GTAP-W.

	Dry hydrologic condition			Average hydrologic condition			Wet hydrologic condition		
	Real GDP		Return to unskilled labour (%)	Real GDP		Return to unskilled labour (%)	Real GDP		Return to unskilled labour (%)
	%	US$ million		%	US$ million		%	US$ million	
Egypt	0.1	86	0.1	~0.0	−15	~0.0	~0.0	25	~0.0
Ethiopia	12.2	2204	9.9	11.3	2033	8.0	10.4	1879	6.9
Sudan (pre-2011)	2.3	441	10.3	1.5	277	5.0	0.6	118	1.4
Total		2731			2294			2022	

Table 9
Predicted percent change in household income and consumption expenditures in the Eastern Nile basin countries relative to the baseline year 2000 based on GTAP-W.

	Dry hydrologic condition		Average hydrologic condition		Wet hydrologic condition	
	Household income	Household consumption expenditure	Household income	Household consumption expenditure	Household income	Household consumption expenditure
Egypt	0.1	0.1	~0.0	~0.0	~0.0	~0.0
Ethiopia	13.3	10.7	10.5	9.8	8.9	9.1
Sudan (pre-2011)	7.7	2.2	3.8	1.3	1.2	0.5

average and wet hydrological conditions. The GERD also generates benefits in terms of lower market prices of agricultural products, increased household income and consumption expenditures. Moreover, the dam improves the real return to unskilled labor and hence contributes to poverty alleviation in the basin.

The substantial economic benefits the GERD generates in Ethiopia mainly emanate from the combined change in the capital stock, domestic saving and immense increase in hydropower supply. The GERD offers Sudan significant economic benefits as it creates regulated flow in the Nile River and as a result ensures increased irrigation water supply. Besides Sudan gains economic benefits from enhanced power generation in its power plants due to reduced sediment load with the GERD operating upstream. The effect of the GERD on Egypt's power supply is found to be limited, it slightly reduces power supply during average hydrological conditions, also because the GERD operation for hydropower generation is a non-consumptive water use and hydropower accounts for a relatively small proportion of the total power supply in the country. Thus, economic growth in Egypt remains more or less stable. Overall, results based on multiple economic indicators considered in this study reveal that Egypt's economy remains stable, suggesting that GERD has no negative impact on the country. Egypt's energy-constrained economy would however benefit substantially if the Eastern Nile countries institute a basin-wide power trade scheme whereby Egypt imports part of the enormous amount of hydropower generated from the GERD.

The value-added of the coupled model employed in this study is assessed by comparing the results of the model to those of two comparable partial equilibrium (PE) models (Arjoon et al., 2014; Whittington et al., 2005) and one CGE model (Kahsay et al., 2015). The estimated economic benefits based on the PE and CGE models are found to be less when evaluated separately compared to the hybrid coupled model. The coupling of the PE-CGE models allows us to take advantage of the complementary capabilities of the two models at different levels of detail and at different spatial scales, and hence provides a more complete and comprehensive assessment of the net economic benefits involved. At the same time it is important to point out that the PE model is used for longer term planning purposes to determine the allocation policies throughout the system under contrasting hydrologic conditions. The ultimate goal of developing and applying the hybrid coupled model in this study was to assess the hydrologic and economic impacts of a new dam, not to support the daily operation of the whole water system. The latter would have required more

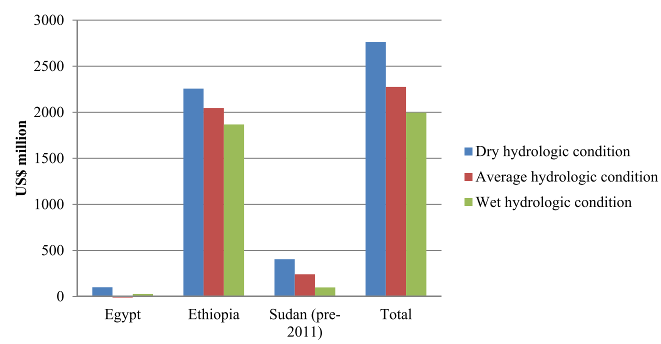

Fig. 5. Expected welfare effects of the GERD in the Eastern Nile countries relative to the baseline year 2000 based on GTAP-W.

detailed spatial and temporal data and model simulations. Water allocations to irrigation schemes may vary in space (irrigation node) and time (year), and our results allow us to determine the reliability of supply for various development scenarios, which can then be used to analyze the trade-off between for example irrigation development and the reliability of water supply. Solving the water resources allocation problem in the Eastern Nile River basin using monthly time steps (we account for intra-annual variability of hydrologic conditions for crop and hydro production) is computationally challenging. Working in daily time steps is, to the best of our knowledge, impossible mostly due to the lack of hydro-meteorological data. Simplifications are therefore unavoidable for the longer term planning of hydraulic infrastructure in large-scale water systems.

The overall results of the study are consistent with the findings of previous studies (Strzepek et al., 2008; Aydin, 2010; Kahsay et al., 2018). The findings of the study presented here reveal, like previous studies, that hydropower dams enhance economic growth and improve welfare. Only the findings by Ferrari et al. (2013) seem to indicate that the GERD investment would slow down economic development in Ethiopia, among others due to the risk of 'Dutch disease'.[1] Unlike the study by Ferrari et al. (2013) who conducted a preliminary assessment

[1] Appreciation of the real exchange rate due to increased export of electricity generated from the GERD, leading to a decline in the country's current exporting sectors by making them less competitive on the export market.

of the possible economic effects of the GERD on the Ethiopian economy, this study demonstrates a thorough analysis of the basin-wide economic effects of the GERD taking into account the economic interactions between the Eastern Nile countries and the integrative nature of the Blue Nile River basin on which the dam is being built.

The coupled modeling approach applied in this study combines the strengths of partial and general equilibrium models and hence provides a methodological advantage over previous modeling approaches in that water allocation is first optimized in a more realistic bottom-up hydro-economic engineering model and these results are subsequently used to assess the wider direct and indirect impacts of the GERD on the Eastern Nile economies. The coupling of the two modeling approaches increases the credibility of the results on the economy-wide impacts of dams.

The results of the stochastic PE model employed to design the simulation scenarios for the GTAP-W model are similar, but not identical to those reported in other studies (Goor et al., 2010; Arjoon et al., 2014; Digna et al., 2018). The differences are mainly due to changes to the baseline and input data in the agricultural sector, which were made consistent in this study with the data used for the CGE model based on the IMPACT data. Besides, the SDDP results used in this study, like the stated studies, reveal that irrigation water use increases in Sudan and remains more or less unchanged in Egypt and Ethiopia. As indicated earlier, the PE model was implemented assuming full cooperation among riparian countries. This assumption will be relaxed in future work to assess the direct and indirect benefits of transboundary cooperation in the Eastern Nile River basin using the proposed PE-CGE approach. Our analysis is further more limited in the sense that the CGE model is informed by the PE model, but not (yet) the other way around. The latter would possibly allow us to consider the broader economy-wide impacts of water allocation optimization at water-system scale. Incorporating the feedback of information from the CGE model to the PE model and testing the convergence of the models is deferred to future research.

Appendix A. Regional aggregation based on the GTAP Africa database

Region	Description
Ethiopia	Ethiopia
Sudan (pre-2011)	Sudan, including South Sudan
Egypt	Egypt
Equatorial Lakes Region	Democratic Republic of Congo (DRC), Uganda, Kenya, United Republic of Tanzania
Rest of North Africa (Rnf)	Morocco, Tunisia, Rest of North Africa
Rest of Sub-Sahara Africa	Cote d'Ivoire, Senegal, Rest of WAEMU, Ghana, Nigeria, Rest of ECOWAS, Cameroon, Rest of CAEMC, Rest of SADC, Rest of COMESA, Botswana, South Africa, Rest of South African CU, Madagascar, Malawi, Mauritius, Mozambique, Zambia, Zimbabwe, Rest of Sub-Saharan Africa
Rest of the World	Oceania, East Asia, Southeast Asia, South Asia, North America, Latin America, European Union 25, Rest of Europe, Middle East,

WAEMU: West African Economic and Monetary Union.
ECOWAS: Economic Community of West African States.
CAEMC: Central African Economic and Monetary Community.
SADC: South African Development Community.
COMESA: Common Market for Eastern and Southern Africa.
CU: Customs Union.

Appendix B. Sectoral aggregation based on the GTAP Africa database

Sector	Description
I. Agricultural Sectors	
Paddy	paddy
Wheat	wheat
Cereal	Cereal grains not elsewhere classified (nec),
Other crops	Plant-based fibers; crops nec; processed rice,
Vegetables and fruits	Vegetables, fruit, nuts
Oilseeds	Oil seeds
Sugar	Sugar cane, sugar beet
Livestock and meat products	Cattle, sheep, goats, horses; animal products nec; raw milk; wool, silk-worm, cocoons; meat: cattle, sheep, goats, horses; meat products nec;
II. Non-agricultural sectors	
Coal	Coal
Crude	Oil
Gas	Gas; gas manufacturing, distribution
Petroleum	Petroleum, coal products
Electricity	Electricity
Processed food	Vegetable oils and fats; dairy products; sugar; food products nec; beverages and tobacco products
Extraction and manufacturing	Forestry; fishing; minerals nec; textiles; wearing apparel; leather products; wood products; paper products, publishing; chemical, rubber, plastic prods; mineral products nec; ferrous metals; metals nec; metal products; motor vehicles and parts; transport equipment nec; electronic equipment; machinery and equipment nec; manufactures nec;
Water	Water
Services	Construction; trade; transport nec; sea transport; air transport; communication; financial services nec; insurance; business services nec; recreation and other services; public administration, defense, health, education; dwellings

Explanatory note: nec means 'not elsewhere classified'.

Appendix C. The effect of GERD operation on hydropower generation in Egypt

Hydropower plant	Power generation without GERD(TWh)			Power generation with GERD (TWh)			Change in power generation due to GERD (%)		
	Hydrologic condition			Hydrologic condition			Hydrologic condition		
	Dry	Average	Wet	Dry	Average	Wet	Dry	Average	Wet
HAD	4.5887	7.3426	9.7898	4.4386	6.906	10.182	−3.3	−5.9	4.0
OAD	3.9731	4.4617	4.7838	4.7838	4.7838	4.7838	20.4	7.2	0.0
Esna	0.8028	0.8646	0.88,458	0.88,458	0.88,458	0.88,458	10.2	2.3	0.0
Total	**9.3646**	**12.6689**	**15.45,818**	**10.10,698**	**12.57,438**	**15.85,038**	**7.9**	**−0.7**	**2.5**

Appendix D. Estimated change in irrigation water allocation (km^3) due to GERD based on the SDDP model

Crops	Without GERD								
	Dry hydrologic condition			Average hydrologic condition			Wet hydrologic condition		
	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan
Rice	13.00	0.00	0.05	13.00	0.00	0.06	13.00	0.00	0.06
Wheat	11.12	0.00	0.71	11.12	0.00	0.78	11.12	0.00	0.79
Other cereals	8.37	0.03	6.43	8.37	0.03	8.00	8.37	0.00	9.52
Other crops	12.79	0.00	0.28	12.79	0.00	0.33	12.79	0.00	0.43
Fruits & vegetables	5.57	0.06	1.13	5.57	0.06	1.20	5.57	0.00	1.20
Oilseeds	0.24	0.01	3.09	0.24	0.01	3.43	0.24	0.00	3.68
Sugar cane, Sugar beet	2.64	0.06	1.29	2.64	0.06	1.63	2.64	0.00	1.67
Total	53.73	0.17	12.97	53.73	0.17	15.44	53.73	0.00	17.35

Crops	With GERD								
	Dry hydrologic condition			Average hydrologic condition			Wet hydrologic condition		
	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan
Rice	13.00	0.00	0.06	13.00	0.00	0.06	13.00	0.00	0.06
Wheat	11.12	0.00	0.79	11.12	0.00	0.79	11.12	0.00	0.79
Other cereals	8.37	0.03	10.13	8.37	0.03	10.36	8.37	0.03	10.39
Other crops	12.79	0.00	0.49	12.79	0.00	0.49	12.79	0.00	0.49
Fruits & vegetables	5.57	0.06	1.16	5.57	0.06	1.20	5.57	0.06	1.20
Oilseeds	0.24	0.01	3.39	0.24	0.01	3.44	0.24	0.01	3.68
Sugar cane, Sugar beet	2.64	0.06	1.55	2.64	0.06	1.67	2.64	0.06	1.67
Total	53.73	0.17	17.57	53.73	0.17	18.01	53.73	0.17	18.29

Appendix E. The predicted change in water demand in irrigated agriculture (km^3) in the Eastern Nile countries due to GERD operation relative to the baseline year 2000 based on GTAP-W

Crops	Without GERD								
	Dry hydrologic condition			Average hydrologic condition			Wet hydrologic condition		
	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan
Rice	13.00	0.00	0.05	13.00	0.00	0.06	13.00	0.00	0.06
Wheat	11.12	0.00	0.71	11.12	0.00	0.78	11.12	0.00	0.79
Other cereals	8.37	0.03	6.43	8.37	0.03	8.00	8.37	0.03	9.52
Other crops	12.79	0.00	0.28	12.79	0.00	0.33	12.79	0.00	0.43
Fruits & vegetables	5.57	0.06	1.13	5.57	0.06	1.20	5.57	0.06	1.20
Oilseeds	0.24	0.01	3.09	0.24	0.01	3.43	0.24	0.01	3.68
Sugar cane, Sugar beet	2.64	0.06	1.29	2.64	0.06	1.63	2.64	0.06	1.67
Total	**53.73**	**0.17**	**12.97**	**53.73**	**0.17**	**15.44**	**53.73**	**0.17**	**17.35**

Crops	With GERD								
	Dry hydrologic condition			Average hydrologic condition			Wet hydrologic condition		
	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan	Egypt	Ethiopia	Sudan
Rice	13.00	0.00	0.06	13.00	0.00	0.06	13.00	0.00	0.06
Wheat	11.12	0.00	0.78	11.12	0.00	0.79	11.12	0.00	0.79
Other cereals	8.37	0.03	8.79	8.37	0.03	9.40	8.37	0.03	10.06
Other crops	12.79	0.00	0.49	12.79	0.00	0.49	12.79	0.00	0.49

Fruits & vegetables	5.57	0.06	1.16	5.57	0.06	1.20	5.57	0.06	1.20
Oilseeds	0.24	0.01	3.40	0.24	0.01	3.45	0.24	0.01	3.69
Sugar cane, Sugar beet	2.64	0.06	1.41	2.64	0.06	1.64	2.64	0.06	1.67
Total	**53.73**	**0.17**	**16.08**	**53.73**	**0.17**	**17.03**	**53.73**	**0.17**	**17.96**

Appendix F. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2019.03.007.

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